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Advances and Frontiers in Sedimentology Research

Min Mao[1,2]

[1] School of Earth Sciences and Engineering, Xi' an Shiyou University, Xi' an, Shaanxi 710065, China

[2] Shanxi Key Laboratory of Petroleum Accumulation Geology, Xi' an, Shaanxi 710065, China

Abstract

In the past three years, sedimentology has witnessed multi-dimensional breakthroughs in theoretical paradigms, technical methods, and application fields. The theoretical framework centered on the "source - sink - transport" system has been further refined, and key progress has been made in the research of deep-water sedimentary processes, the formation and storage mechanisms of deep and ultra-deep carbonate rocks, and fine-grained sedimentary systems. The deep integration of high-precision chronology, high-resolution geophysical exploration, and artificial intelligence technologies has facilitated a leap from qualitative description to quantitative forward modeling of sedimentary processes. Meanwhile, the cross-fusion of sedimentology with global change, planetary geology, and unconventional energy exploration has deepened, forming a new understanding of "sedimentary sphere science". This article systematically reviews the core progress in these areas, focusing on the expansion of the source-sink system, the innovation of deep-water sedimentary dynamic mechanisms, the microscopic breakthroughs in carbonate rocks and fine-grained sediments, and the intelligent transformation of technical methods. It also looks forward to the future development direction of the discipline, aiming to provide references for theoretical innovation and resource and environmental applications in sedimentology.

Keywords

Sedimentology; Source-Transport-Sink System; Deep-Water Sedimentation; Deep Carbonate Rocks; Fine-Grained Sedimentation; Artificial Intelligence; Sedimentary Sphere Science.

1. Introduction

Sedimentology, as an important branch of geoscience, has always been closely linked to the demands of resource exploration, technological innovation, and research on global environmental changes. Since 2024, with the expansion of oil and gas exploration into deeper and ultra-deep layers, unconventional areas, as well as the continuous deepening of exploration into deep-time paleoclimate, paleoseismology, and planetary geology, the research scale of sedimentology has achieved full coverage from nanoscale microscopic pores to global-scale sedimentary systems. The research paradigm has completed the transformation from "descriptive analysis" to "cause mechanism analysis" and "quantitative process simulation". The limitations of the traditional "source - sink" model have gradually become apparent, and the "source - sink - pathway" global framework has been established; the driving mechanism of deep-water sedimentation has broken through the single perception of sea level changes, and the combined control effect of tectonics - magmas - sediment supply has been confirmed; the formation and storage mechanisms of deep - ultra-deep carbonate rocks and the oil and gas enrichment laws of fine-grained sediments have been studied, providing core theoretical support for energy reserve increase and production enhancement. Based on the latest research results from 2024 to 2026, this article systematically summarizes from four aspects: core

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theoretical progress, key breakthroughs in key fields, technological method innovations, and future prospects, presenting the contemporary development pattern of sedimentology.

2. Expansion and Innovation of the Core Theoretical Framework

2.1. "Source-Destination-Transit" System: Global Cognition Beyond the Classical Model

The classic "source-sink" model is unable to cover the geological processes in inactive sedimentary areas. A study published in Geology in 2025, by integrating global remote sensing and geological data, has for the first time constructed a global database of the "source-sink-transport" system, filling the gap of traditional theories. This research clearly indicates that the Earth's land surface is dominated by "source areas", while "passage areas" (inactive sedimentary areas) and "sink areas" account for relatively smaller proportions. Regions such as deserts, due to the lack of significant sediment transport, are not applicable to the classic "source-sink" model. This framework expands the "erosion - transportation - deposition" process of sediments into a complete chain of "source area erosion - passage zone transportation - retention in the bypass area - burial in the sink area", emphasizing the dynamic differentiation of the "passage zone" and the sediment inertness of the "bypass area", providing a new theoretical perspective for global surface process research.

In the study of oil and gas-bearing basins, "source-sink system sedimentology" has become an independent branch. Its core advantage lies in breaking through the limitations of traditional research on the sedimentary area, integrating the erosion area, transportation area and sedimentary area as a whole system, establishing the correlation between landforms and underground geology, and achieving precise prediction of sedimentary bodies through quantitative analysis. Combined with forward simulation technology, this theory has been successfully applied to the evaluation of favorable zones and well placement in continental basin shale oil and gas, promoting the transition of the source-sink process from static reconstruction to dynamic evolution.

2.2. Sedimentation Science: A New Paradigm for the Development of the Discipline

The century-long development of sedimentology is essentially a process of continuously expanding research scales and continuously improving theoretical systems. The review article in the Journal of Sedimentology in 2025 proposed the core assertion of "from sedimentology to sedimentary circle science", defining the sedimentary circle as the layer composed of sediments and sedimentary rocks on the Earth's surface. Its interaction with the atmosphere, hydrosphere, biosphere and lithosphere controls the global element cycle, climate evolution and the formation of mineral resources[1].

This paradigm shift highlights the systematic and coupled nature of sedimentary processes: Taking the Permian ultra-deep carbonate rocks in the Sichuan Basin as an example, through core observation, micro-area isotope analysis, and U-Pb dating techniques, the coupling relationship between multiple periods of saline diagenetic fluid activities and reservoir formation was revealed, proving the linkage effect of diagenesis within the sedimentary system and the external tectonic-climatic system. The proposal of the sedimentary system concept has elevated sedimentology from a single-discipline study to the level of Earth system science, providing a new theoretical framework for deep-time paleoenvironmental reconstruction and global carbon cycle research.

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3. Breakthroughs in Key Research Areas

3.1. Deep-water Sedimentary System: Detailed Analysis of the Driving Mechanism and Configuration Evolution

Deep-water sedimentation serves as a crucial link connecting the land and the deep sea, and its sedimentary records exhibit high sensitivity to tectonic, magmatic, and climatic events. In the past three years, significant breakthroughs have been made in the study of deep-water sedimentation in terms of configuration evolution, driving mechanisms, and dynamic processes.

In the study of the deep-water accumulation system at the margin, the case of the Arc-front Basin in Xizang Jikara overturned the traditional understanding. The research team, through the detailed description of a continuous stratigraphic sequence of nearly 3 km, established a high-precision chronological stratigraphic framework from 99.0 Ma to 93.8 Ma, revealing the evolutionary pattern of this deep-water system from the mid-outer fan lobate bodies to the slope-bottom - proximal basin plain, and ultimately evolving into a restricted channel complex. The key breakthrough lies in the confirmation that the dominant driving force of accumulation is the peak event of the Kangding Arc magmatic activity, the increase in sediment flux caused by tectonic contraction, rather than the traditional view of sea-level changes. The "sediment supply-driven" effect far exceeds the influence of the increase in the available space, providing a comparative template for the study of deep-water sedimentation at convergent margins worldwide[2].

In the context of deep-sea dynamic sedimentation processes, research in the northern part of the South China Sea has revealed the shaping effect of internal waves on giant sediment waves. Through high-resolution seismic data and long-term hydrological observations, it has been confirmed that in the "critical zone" where the ratio of the slope of the seabed to the velocity vector angle of the internal wave group approaches 1, the internal wave energy dissipation strongly disturbs the seabed boundary layer, driving the resuspension and transport of fine-grained sediment, and forming sediment waves with a wave height of 50 meters and a wavelength of 1.4 kilometers. This discovery has established the important position of internal waves in the evolution of continental margin landforms, deepened the understanding of the deep-sea "source-sink" process, and provided a scientific basis for the selection of seabed engineering sites.

3.2. Deep-to-ultra-deep Carbonate Rock Reservoirs: Formation and Preservation Mechanisms

As oil and gas exploration extends to deeper and ultra-deep layers, the development and preservation mechanisms of carbonate rock reservoirs have become a research hotspot. From 2024 to 2026, studies in key regions such as the Sichuan Basin and the Tarim Basin have clarified that the formation of ultra-deep carbonate rock reservoirs is controlled by the triple coupling of sedimentary facies control, diagenetic modification, and structural preservation.

Taking the Dengying Formation of the Chongzhong Anticline in the Sichuan Basin as an example, through micro-area carbon and oxygen isotope analysis, fluid inclusions, and U-Pb dating techniques, the temporal and spatial patterns of multiple periods of saline water diagenetic fluid activities were revealed. The study found that under ultra-deep conditions, the primary pores formed by early constructive diagenesis (such as dolomitization and dissolution) were transformed into fracture-pore composite reservoir spaces by late tectonic fractures, while the periodic activities of salt water slowed down the cementation and filling of pores, which was the key to the preservation of the reservoir. At the same time, progress has been made in the quantitative evaluation technology of reservoir heterogeneity of deep carbonate rocks. Through digitalization of core thin sections and artificial intelligence recognition, the precise

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characterization of pore types, fracture density, and permeability was achieved, providing core parameters for deep oil and gas development[3].

Research on carbonate sedimentation under extreme climatic conditions has also made significant breakthroughs. The research conducted by Southwest Petroleum University discovered the largest ooids under the "super greenhouse" climate of the Cambrian period. Through high-resolution two-dimensional elemental imaging, it revealed the P–Fe co-distribution characteristics, confirming that microbial-induced mineralization and anaerobic metabolic activities promoted the rapid lithification of ooid laminae. The formation of the giant ooids is the result of the coordinated regulation of physical, chemical and biological factors, and its sedimentary record provides a new perspective for understanding carbonate sedimentary systems under extreme climates.

3.3. Fine-grained Sedimentation and Unconventional Hydrocarbons: Sedimentary Characteristics and Hydrocarbon Accumulation Patterns

The development of fine-grained sedimentology has directly promoted the exploration and development of onshore shale oil and gas. In the past three years, research has focused on the temporal and spatial differentiation of onshore shale sedimentation, as well as the coupling relationship between the microscopic pore structure and hydrocarbon potential.

Studies on China's oil and gas-bearing basins have shown that the sedimentary environment of continental shale is jointly controlled by paleoclimate, paleo-water depth and paleo-river systems. The reservoir properties of fine-grained sedimentary rocks in lacustrine layers exhibit significant inter-layer differences. Through core observation, X-ray diffraction and nano-CT technology, it was discovered that the organic matter-rich layers and brittle mineral layers in shale are interlayered. Changes in the thickness of the laminae directly affect the spatial distribution of porosity and permeability, thereby controlling the enrichment of oil and gas and its recoverability. At the same time, progress has been made in the study of diagenesis of fine-grained sediments, clarifying the temporal sequence relationship between thermal evolution degree, clay mineral transformation and organic matter hydrocarbon generation, providing a theoretical basis for the prediction of shale oil and gas sweet spots[4].

In the study of the carbon cycle of fine-grained marine sediments, the case of the Bay of Bengal has revealed the regulatory mechanisms of organic carbon burial. The research found that fine particles (2.5 - 10 μm) are conducive to the sealing of terrestrial organic matter under the influence of monsoon ocean currents; the composition of clay minerals plays a crucial role in the preservation of organic carbon. Illite forms a "micro-environment isolation layer" by encapsulating organic matter, reducing the microbial degradation rate by 40%, while the porous structure of montmorillonite leads to a loss rate of 65% of remote organic carbon. Around 9.5 thousand years ago, the rise in sea level and the stratification of water bodies caused by strong monsoon winds led to a decrease in organic carbon burial by more than 50%. This achievement provides new insights into the coupled study of paleoclimate and marine carbon reservoirs.

3.4. The Interdisciplinary Expansion of Sedimentology: Paleoenvironment and Planetary Geology

The application of sedimentology in the fields of paleoenvironmental reconstruction and planetary geology is becoming increasingly widespread, forming new research growth points. In the study of ancient environments at high latitudes, the analysis of sediment flux in the Okhotsk Sea revealed the environmental evolution patterns over the past 30,000 years. Through the analysis of grain size and elemental geochemistry of 10 sediment cores, it was found that the sediment flux was high in the central and southern parts of the sea during the last ice age and low in the northern part, while since the end of the last ice age, the trend was

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reversed. This temporal and spatial difference is comprehensively controlled by sea ice, bottom currents, river runoff and sea level changes, and is closely related to the solar radiation at high latitudes in the Northern Hemisphere[5].

In the field of planetary sedimentology, significant breakthroughs have been made in the study of ancient river fans on Mars. Through a systematic investigation of 345 terrestrial river fans, a highly accurate prediction model was established, and it was calculated that the average annual surface runoff of the ancient river fan in the Holden crater on Mars reached 1,882,800 cubic meters. This confirmed that the water source of the ancient river fan included atmospheric precipitation and glacial meltwater. This research not only provided crucial evidence for the study of ancient water circulation and climate on Mars, but also deepened the understanding of the evolution history of arid regions on Earth through the comparison of extraterrestrial sedimentary records.

4. Intelligentization and High-precision Transformation of Technical Methods

4.1. High-precision Chronology Technology: Time Constraints on Sedimentary Processes

The establishment of a high-precision chronological stratigraphic framework is the core prerequisite for the analysis of sedimentary processes. In the past three years, the combined application of zircon U-Pb dating, volcanic ash dating, and radiocarbon dating has solved the problem of difficult dating in deep-water strata and fine-grained sedimentary strata.

In the study of the Dayigao Frontal Basin in Xizang, by using the maximum sedimentary age of 3 layers of volcanic ash and 5 sandstone samples, the age of the deep-water accumulation sequence was precisely limited to the Late Cretaceous, with an error controlled within 0.2 Ma. In the study of the ancient earthquakes in the subduction zone, through radiocarbon dating, the formation time of the turbidite rock sequence was precisely matched with the ancient earthquake events, with a time resolution of the order of hundreds of years [6]. The application of these techniques has made it possible to calculate the quantitative evolution rate and event frequency of the sedimentary process, promoting the transition of sedimentology from "qualitative evolution" to "quantitative timing".

4.2. High-resolution Detection and Microscopic Analysis Technology: Precise Depiction of Multi-scale Deposition Characteristics

The innovation of geophysical exploration and microscopic analysis techniques has enabled the full-scale depiction of sedimentary systems from macroscopic configurations to microscopic pores. At the macroscopic scale, high-resolution two-dimensional/three-dimensional seismic data and autonomous underwater vehicles' bathymetric measurement technology can clearly identify deep-water channels, leaf bodies, and the geometric shapes and spatial distribution of sediment waves; at the microscopic scale, nano CT, high-resolution scanning electron microscopy, and two-dimensional elemental imaging techniques can precisely characterize the pore structure of carbonate rocks, the grain layer characteristics of ooids, and the organic matter distribution of shale[7].

Taking the study of ultra-deep carbonate rocks as an example, through micro-area isotope analysis and fluid inclusions temperature measurement, the source and activity time of the diagenetic fluids can be traced; in the study of fine-grained sediments, the nano-CT technology enables the three-dimensional visualization of nanopores in shale, revealing the spatial correlations between pores, organic matter, and clay minerals. The integrated application of these technologies provides direct microscopic evidence for the interpretation of sedimentary genesis mechanisms[8].

ISSN: 2710-0723

4.3. Artificial Intelligence and Forward Simulation: Quantitative Prediction of Sedimentary Processes

The combination of artificial intelligence technology and forward simulation of sedimentary processes is the core of the technological innovation in sedimentology in recent years. In reservoir evaluation, the intelligent core sample analysis system based on machine learning can automatically identify the mineral composition, pore types and fracture characteristics in core thin sections, and achieve rapid quantitative evaluation of permeability and porosity[9]. In the study of source-sink systems, by constructing a multivariate statistical model of ancient landforms, ancient climates and sediment supply, combined with forward simulation technology, the erosion, transportation and deposition processes of sediments from source to sink can be dynamically reconstructed, thereby improving the prediction accuracy of sedimentary bodies[10].

Meanwhile, the application of artificial intelligence in the identification of sedimentary facies has achieved a breakthrough. By training a correlation model between seismic attributes and sedimentary facies, automatic identification and spatial distribution prediction of deep-water sedimentary facies have been realized, providing technical support for the selection of favorable exploration areas in oil and gas exploration. The innovation of forward modeling technology enables the visualization of the dynamic evolution process of the source-sink system, overcoming the limitations of traditional static reconstructions.

5. Summary

From 2024 to 2026, sedimentology witnessed a series of landmark advancements in both theory, methods, and application. The proposal of the "source - sink - transit" system and the concept of sedimentary cycle science have refined the core theoretical framework of sedimentology; studies on deep-water sedimentation, deep carbonate rocks, and fine-grained sediment have revealed the multi-factor driving mechanisms and microscopic evolution laws of sedimentary processes; the application of high-precision chronology, artificial intelligence, and forward modeling techniques has facilitated the transformation of sedimentology from qualitative description to quantitative prediction. In the future, with the development of Earth system science and continuous technological innovations, sedimentology will play an even more crucial role in resource exploration, global change research, and planetary geological exploration, providing core scientific support for humanity's understanding of the Earth, resource development, and response to environmental changes.

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